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Enhancing the Performance of BICPV Systems Using Phase Change Materials

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Abstract. Building Integrated Concentrated Photovoltaic (BICPV) systems have three main benefits for integration into built environments, namely, (i) generating electricity at the point of use (ii) allowing light efficacy within the building envelope and (iii) providing thermal management. In this work, to maintain solar cell operating temperature and improve its performance, a phase change material (PCM) container has been designed, developed and integrated with the BICPV system. Using highly collimated continuous light source, an indoor experiment was performed. The absolute electrical power conversion efficiency for the module without PCM cooling resulted in 7.82% while using PCM increased it to 9.07%, thus showing a relative increase by 15.9% as compared to a non- PCM system. A maximum temperature reduction of 5.2°C was also observed when the BICPV module was integrated with PCM containment as compared to the BICPV system without any PCM containment.

INTRODUCTION

Building-integrated photovoltaics (BIPV) is proving to be the most rapidly emerging technology of the solar industry globally with an estimated capacity growth of about 50% or more from 2011 to 2017.[1] Some of its applications can be as a shading device for windows, semi-transparent glass façade, building exterior cladding panel and parapet unit or roofing system.[2] BICPV systems concentrate the solar radiation with curved mirrors (reflective-types) or lenses (refractive-types) and offer advantages over conventional flat panel systems in improved electrical conversion efficiency, better use of space, option of recycling the component materials and use of less toxic products associated with production of PV cells.[3] Low geometrical concentration ratios (Cg) provide less than 10 x concentrations and are mostly static in nature which provides simplicity of building integration and design.

An in-house BICPV system has been developed which can be easily integrated with solar cells into glazing façades and has advantages in; (i) maintaining a level of transparency of the glazing windows allowing the penetration of the daylight, (ii) producing low-cost electricity increasing the energy efficiency of buildings and (iii) extremely low solar heat gain. It can save more than 60% of solar cells used in glass PV. The incident sunrays on the façades or windows are concentrated by Square Elliptical Hyperboloid (SEH) concentrators to be focused in smaller areas of 1cm^2 silicon solar cells.[4] Gaps are created in SEH concentrators due to top elliptical shape of concentrators for semi transparency effect allowing daylight penetration. This unique optical concentrating design enables high transparency and high efficiency delivering hassle-free power from window as can be seen from Fig. 1 (b).

However, BICPV faces challenge with rise in temperature, manifested as electrical efficiency loss and overheating. This efficiency loss is mainly due to a decrease in open-circuit voltage (V_{oc}), which has negative

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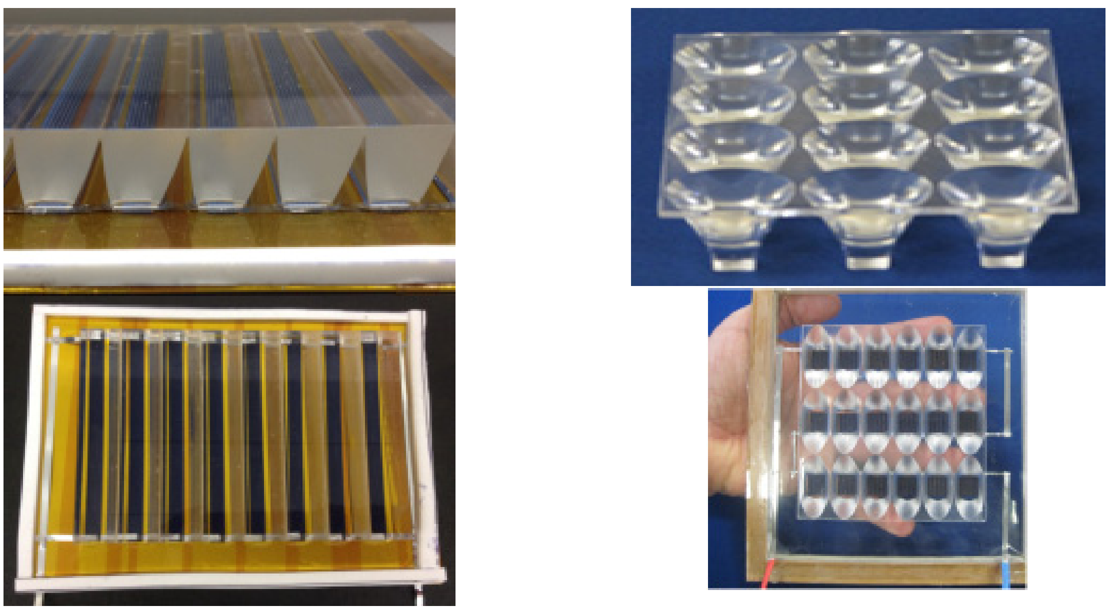
temperature coefficient. Low cost silicon based photovoltaic cells convert a small (less than 20%) portion of the sunlight to electricity.[5] The remaining photons are dissipated in the cells as heat. Efficiency of silicon cells reduces at a rate of approximately 0.45% per degree increase in operating temperature.[6] Along with this temperature control, it is also advisable to have more uniformity of temperature throughout the panel and avoidance of hot spots, which give rise to current mismatch and reduce the overall efficiency of the system.[7]

Therefore, cooling of BICPV modules is essential and is currently achieved via natural air circulation in fins and heat spreaders.[8] Recently emerging PV–PCM (phase change materials) system concept for temperature control gives an opportunity for extending its usage to BICPV systems. In previous studies on BIPV-PCM systems on a 1-D dynamic simulation program developed with MATLAB/SIMULINK®, solved using control-volume based finite-difference scheme, the electrical efficiency showed 10% and thermal efficiency 12% increase with experimental and numerical results in agreement.[9] Employing PCM could passively keep the BICPV temperature within safe operating zones and also collect rejected heat for regeneration. PCM as latent heat storage systems offer high storage density compared to their sensible heat storage counterparts. They undergo reversible transition of phase in continual use, operate isothermally and are available in wide range making them suitable for various concentrations.

This paper details the results of a preliminary indoor experimental investigation of an in-house manufactured BICPV module using linear asymmetric compound parabolic concentrator (Fig. 1 (a)). The thermal regulation and its effect on module performance were tested using an organic paraffin wax based PCM, RT 42 under ambient temperature conditions of 28°- 35°C.



(a) (b)

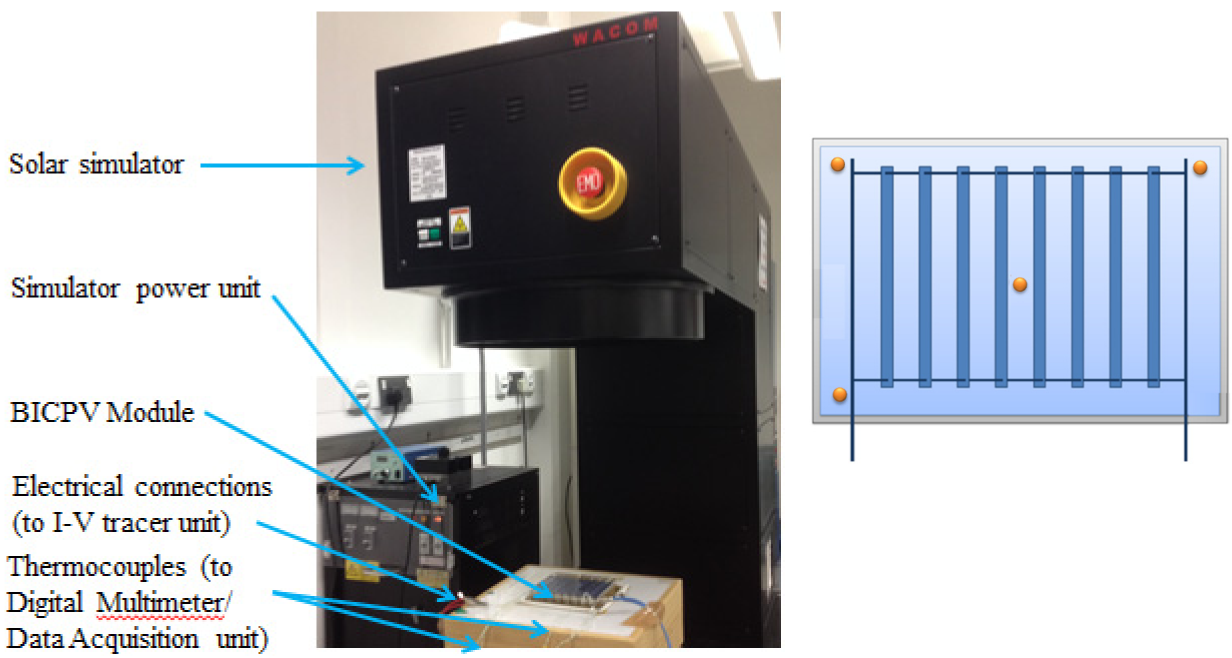
FIGURE 1. Comparison of Present and Previous studies: Side and Plan views of the BICPV module with (a) Aluminium backing and LACP concentrator and (b) Glass backing and SEH concentrator for semi-transparency effect

EXPERIMENTAL METHODS

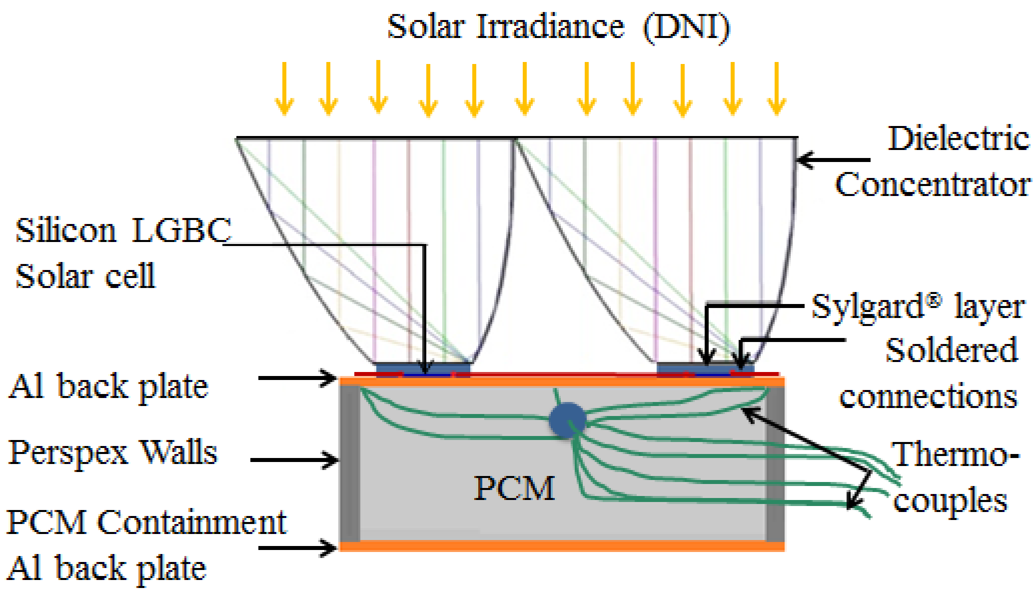
A BICPV– PCM prototype system was designed and fabricated using in-house developed low concentrating lenses (Cg ~ 2.0) using optically clear liquid *Crystal Clear® 200 Clear Urethane Casting Resin* (two-part, with 10:9 mix ratio). Eight LGBC (Laser Grooved Buried Contact) crystalline silicon cells with dimensions 116mm x 6mm were soldered in series connection using thin tin-plated copper strips (Fig. 1 (a)). This module was assembled on aluminium back plate (wrapped with Kapton tape for electrical insulation) for ensuring good thermal conduction. An encapsulant, *Sylgard® 184 Silicone Elastomer*, whose chemical name is *polydimethylsiloxane* elastomer, was mixed in a separate beaker (two-part, with 10:1 mix ratio) and poured over solar cells assembly with concentrating lenses atop, till a uniformly distributed layer was created and left for 48 hours to cure at room temperature. This thin layer of silicone ensures an appropriate optical coupling between the lenses and soldered cells assembly and as an adhesive as well as protective coating from mechanical damages.

An initial test prototype of the PCM containment/heat sink was developed using 13mm thick Perspex sheet (cast *Poly-methyl methacrylate*) with the inner dimensions of 143mmx133mmx38mm. This design was based on heat transfer equations from literature based study[10, 11] and needs further mathematical treatment. Wacom solar simulator with solar intensity of 1000 W/m^2 provided constant irradiation. The experimental set-up in depicted in Fig. 2(a) and details of the system operating in sunlight is shown in Fig. 2(b). A set of four K-type thermocouples were attached to the back side of the aluminium plate (Fig.2 (c)). The locations were strategically chosen to study temperature variations across the centre and different edges of the module. The observations were recorded for 2 hour period at an interval of 10 minutes. Ambient temperature and relative humidity were recorded using *Hygrometer testo608-H1*.

The fabricated BICPV– PCM module is unique and it differs from its previous counterparts[4, 12-14] in a number of ways such as instead of glass back plate for more optical transparency, aluminium plate is used for the purpose of heat collection, removal and possible recovery. Also previously, passive air cooling was the only means of reducing module temperatures which depended on the availability of ambient air, wind speed, climatic conditions and geographic dependency, which is not the case with utilizing PCM for passive cooling. The rationale behind selecting *Crystal Clear® 200* is its suitability for ½" - 3" thick castings, low viscosity which ensures easy mixing, pouring and capability to cure at room temperature with negligible shrinkage. The castings are also UV–resistant and are not brittle, which are ideal for the purpose. Similarly, *Sylgard®* was selected for encapsulation purpose due to its transparency which allows easy inspection of components, flame resistance, good dielectric properties, and rapid, versatile cure processing controlled by temperature.



(a) (b)



(c)

FIGURE 2. (a) Experimental set-up for examining the effect of PCM over power output of a low concentrating BICPV module; (b) Schematics of the thermocouple locations at the rear surface of the module and (c) detailed elevation view of the BICPV-PCM module with Aluminium backing (not drawn to scale)

RESULTS AND DISCUSSIONS

From the I-V and P-V curves for the developed BICPV –PCM system, without and with PCM, as shown in Fig. 3(a) and (b) respectively, it can be seen that there is an increase in both short circuit current and maximum electrical power using PCM. This increase is more predominant for lower temperature current (e.g.: at 35°C). The effect of temperature on the maximum power output generated from the module, I_{sc}, V_{oc} and P_m is as shown in Fig. 4 (a), (b) and (c) respectively. The recorded module central temperature without PCM increases by 22°C (24°C for with PCM) from the ambient 30°C (28°C for with PCM)) and caused a 17.25% (14.8% for with PCM) power loss in the first 30 minutes. It was also observed that there was a highly non-uniform temperature distribution throughout the module, which may cause local hot spots within leading to higher efficiency losses in the long run, and since the solar cells are connected in series, the cell with the smallest output limits the overall output current. The highest temperature (60.9°C without and 58.7°C with PCM) attained at the centre, was 4-5°C higher than the average module temperature in both cases. This could be attributed to the edge effect or end losses happening at corners and sides of the module due to interfacing with the surroundings. It is also deduced that the use of PCM increases the uniformity of temperature throughout (less temperature fluctuations with PCM) which may lead to prolonged module life. The absolute electrical power conversion efficiency for the module without PCM cooling resulted in 7.82% while with the use of PCM in the system, it increased to 9.07%. An overall electrical conversion efficiency improvement of 15.9% was achieved for the BICPV –PCM system as compared to a non –PCM systems whereas maximum temperature difference was 5.2°C. Some important results for comparison of the system with and without PCM are detailed in Table 1. Negative sign implies a decrease in the property using PCM.

TABLE 1. Important data from the BICPV-PCM system

	$T_{c,\,Min}$ (°C)	$T_{c,\,max}$ (°C)	$I_{sc,\,Min}$ (mA)	$I_{sc,\,Max}$ (mA)	$V_{oc,\,Min}$ (mV)	$V_{oc,\,Max}$ (mV)	$P_{m,\,Min}$ (mW)	$P_{m,\,Max}$ (mW)
Without PCM	36.1	60.9	302.1	320.0	3831.0	4532.1	789.1	982.1
With PCM	30.9	58.7	347.8	350.9	3951.2	4658.5	902.0	1112.4
Delta %	-5.2	-2.2	15.1	9.4	3.1	2.8	14.3	13.3

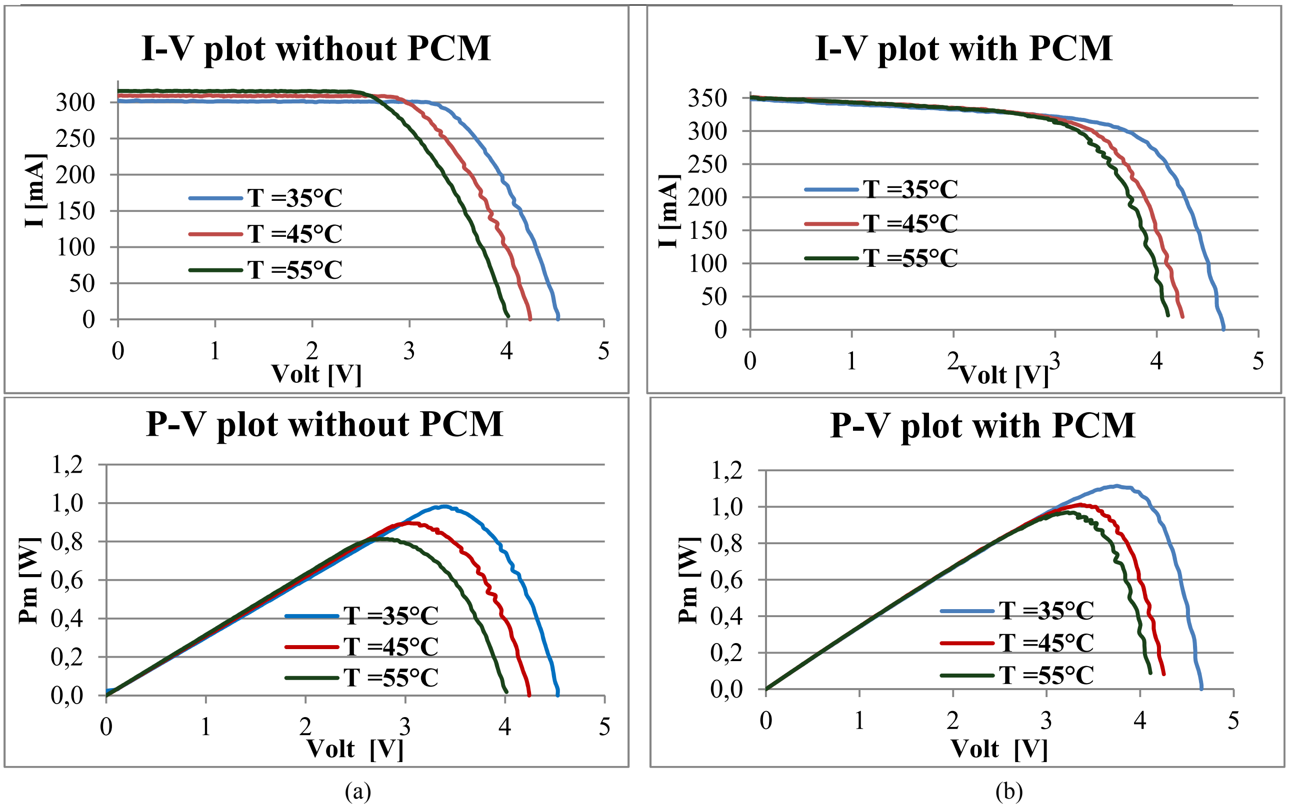
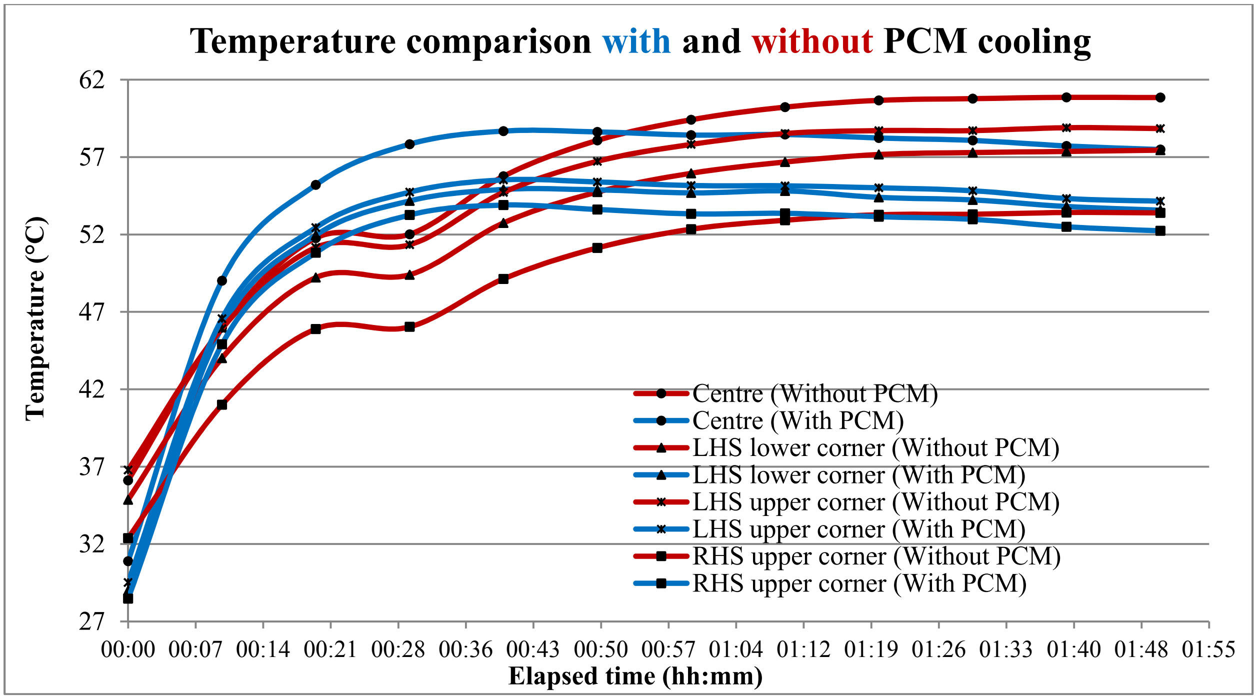
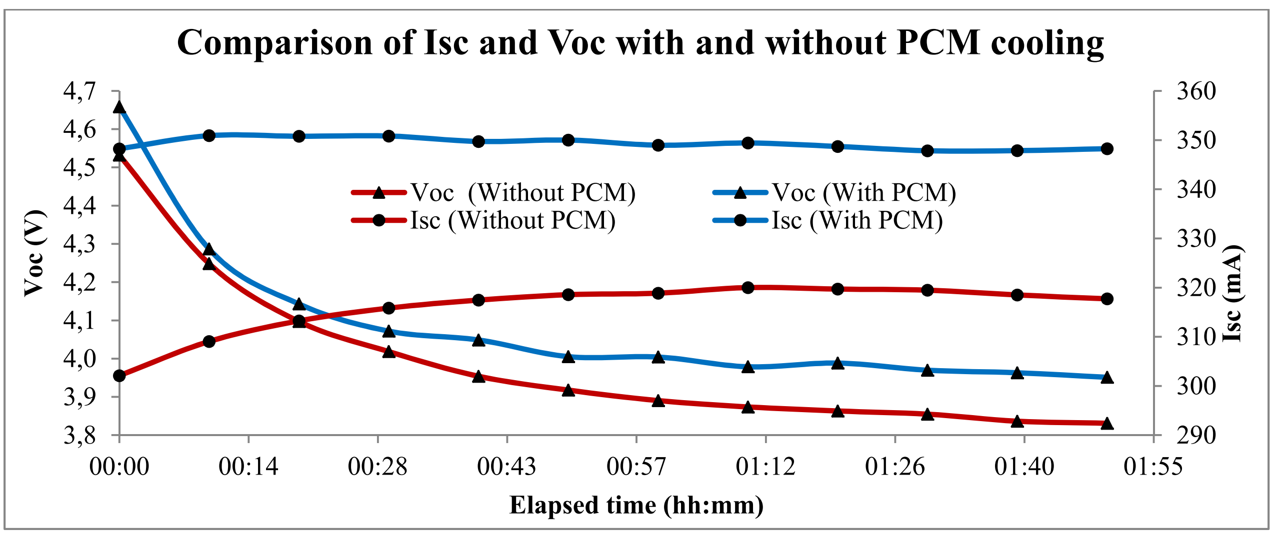


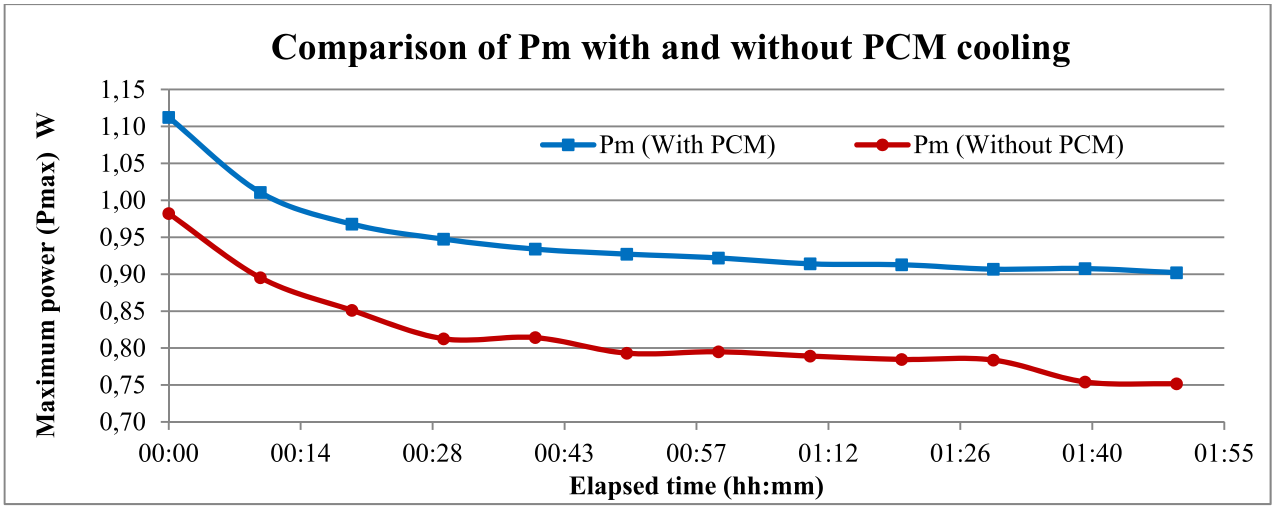
FIGURE 3. I-V and P-V curves for the BICPV module (a) without and (b) with PCM


Temperature comparison with and without PCM cooling
Temperature (°C)
62
57
52
47
42
37
32
27
00:00 00:07 00:14 00:21 00:28 00:36 00:43 00:50 00:57 01:04 01:12 01:19 01:26 01:33 01:40 01:48 01:55
Elapsed time (hh:mm)
Centre (Without PCM)
Centre (With PCM)
LHS lower corner (Without PCM)
LHS lower corner (With PCM)
LHS upper corner (Without PCM)
LHS upper corner (With PCM)
RHS upper corner (Without PCM)
RHS upper corner (With PCM)

(a)


Comparison of Isc and Voc with and without PCM cooling
Voc (V)
4,7
4,6
4,5
4,4
4,3
4,2
4,1
4,0
3,9
3,8
Isc (mA)
360
350
340
330
320
310
300
290
00:00 00:14 00:28 00:43 00:57 01:12 01:26 01:40 01:55
Elapsed time (hh:mm)
Voc (Without PCM)
Isc (Without PCM)
Voc (With PCM)
Isc (With PCM)

(b)



(c)

FIGURE 4. Comparison of BICPV module characterisation parameters with and without PCM (RT42®) w.r.t. time (a) rear side temperature (b) I_{sc} and V_{oc} and (c) P_{max} (Inclination:0°, Intensity:1000W/m^2)

CONCLUSION

BICPV systems have proved to be highly effective in generating electricity for local use and also providing thermal management in the buildings. They provide a simple and cost-effective way of generating more electrical energy with the same amount of solar radiation as compared to a non-concentrating system. The major challenge as a result of concentration is the inevitable increase in operating temperature of solar cells which intensely impacts the system performance by reducing its efficiency. In this scenario, cooling systems become vitally important for keeping cells under safe operating limits and evenly distributing the residual heat flux to avoid local hot spots that further reduce electrical efficiency. PCM have been used for latent heat storage in the past with BIPV applications and proved successful and shown up to 10% electrical efficiency improvement. Their application to BICPV systems for heat removal as well as possible regeneration is proving successful. An initial investigation into an in-house developed test BICPV– PCM prototype system has shown appreciable results with providing 15.9% electrical efficiency improvement in BICPV systems. The absolute electrical power conversion efficiency for the module without PCM cooling resulted in 7.82% while with the use of PCM in the system, it increased to 9.07%. A maximum temperature reduction of 5.2°C was observed in BICPV module integrated with PCM.The experiment could be iterated for longer durations to explore PCM cooling characteristics and with various organic and inorganic PCM with different melting characteristics, to test their efficacies.

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